Penn State Environmental Law Review

Volume 18 | Number 2 Article 5

1-1-2010

Pyrogeography: Lessons for Future Northeastern U.S. Landscape

Erica A.H. Smithwick

Recommended Citation

Erica A. Smithwick, *Pyrogeography: Lessons for Future Northeastern U.S. Landscape*, 18 *Penn St. Envtl. L. Rev.* 155 (2010).

Pyrogeography: Lessons for Future Northeastern U.S. Landscapes

Erica A.H. Smithwick*

Abstract

Future fire events of the northeastern United States are likely to vary in frequency, severity, and spatial distribution. Causes for these shifts can be understood in terms of changes in the geography, climate, fuels, and ignition sources that will govern the distribution of fire on future northeastern landscapes, all of which are projected to be different from current conditions and those of the historical past. I draw upon the well-studied, fire-prone ecosystems of the Greater Yellowstone Ecosystem and the frequently burned ecosystems of southern Africa as case studies to understand the pace and potential ecological consequences of altered fire patterns for the northeastern United States. I conclude by highlighting several lessons relevant for emerging northeastern fire policy, including the need to (1) confront generalities across a variety of ecosystems and disturbance regimes, (2) enable conditions that promote resiliency in the face of change, and (3) manage for key ecological functions.

I. SCIENTIFIC BACKGROUND

A. The Geography of Fire

Fire has played a fundamental role in the Earth system since soon after the appearance of terrestrial plants during the Silurian geologic

---

* Dr. Erica Smithwick is an assistant professor of geography at Penn State University. Professor Smithwick received her B.S. from Tufts University an M.S. from the University of Montana, and a Ph.D. from Oregon State University. Professor Smithwick's research interests center on 1) field- and laboratory-based approaches to understanding ecosystem biogeochemistry following disturbance (especially wildfire) and 2) use of ecosystem process models to forecast effects of disturbance and climate on future carbon and nitrogen cycling in terrestrial ecosystems. Ongoing research activities in her lab are focused on modeling fire-vegetation-climate interactions along the Appalachian Trail and the Greater Yellowstone Ecosystem under climate change.

period (420 million years ago).[1] Since this time, individual fire events have been governed by the confluence of abiotic and biotic factors that determine combustion, including available fuel, weather, and ignition sources. These factors are spatially patterned and temporally variable across heterogeneous landscapes.[2] As a result, geographic perspectives of fire are critical for determining the likelihood of fire at a given location and over a certain period of time. Moreover, regional fire distribution is likely to be driven by the interaction of multiple abiotic and biotic processes rather than by a single factor. Usually, these abiotic and biotic factors interact in complex, often compensatory, ways resulting in patterns that cannot be determined by examining each factor in isolation.[3] For example, despite consistently high fuel loads, fire patterns in the Klamath Mountains in California are constrained by physical features such as topography.[4] Thus, understanding the mechanistic interaction of biotic and abiotic factors in one location, and how these factors vary across space, is critical for projecting future patterns of fire at regional scales.

Similarly, the ecological consequences of fire events are geographically contingent. Ecosystems are affected by fire events through reductions in biomass, changes in soil and microclimate conditions,[5] and shifts in vegetation species composition and wildlife habitat.[6] These effects differ through space and time depending on the

---

[1] *See generally* David Bowman et al., *Fire in the Earth System*, 324 SCI. 481(2009); Andrew J. Scott & Ian J. Glasspool, *The diversification of Paleozoic fire systems and fluctuations in atmospheric oxygen concentration*, 103 PROC. NAT'L ACAD. SCI. U.S. 10861 (2006).

[2] *See generally* Martin P. Girardin et al., *Heterogeneous response of circumboreal wildfire risk to climate change since the early 1900s*, 15 GLOBAL CHANGE BIOLOGY 2751(2009); Brian D. Amiro et al., *Direct carbon emissions from Canadian forest fires, 1959-1999*, 31 CANADIAN J. FOREST RES. 512 (2001).

[3] *See generally* Debra P.C. Peters, *Cross-scale interactions, nonlinearities, and forecasting catastrophic events*, 101 PROC. NAT'L ACAD. SCI. U.S. 15130 (2004); Craig R. Allen & Crawford S. Holling, *Cross-scale Structure and Scale Breaks in Ecosystems and Other Complex Systems*, 5 ECOSYSTEMS 314(2002).

[4] *See generally* Alan H. Taylor & Carl N. Skinner, *Spatial Patterns and Controls of Historical Fire Regimes and Forest Structure in the Klamath Mountains*, 13 ECOLOGICAL APPLICATIONS 704 (2003).

[5] *See generally* Sarah T. Hamman et al., *Relationships between microbial community structure and soil environmental conditions in a recently burned system*, 39 SOIL BIOLOGY & BIOCHEMISTRY 1703(2007); Kevin C. Grady & Stephen C. Hart, *Influences of thinning, prescribed burning, and wildfire on soil processes and properties in southwestern ponderosa pine forests: A retrospective study*, 234 FOREST ECOLOGY & MGMT. 123 (2006).

[6] *See* David R. Foster et al., *Oak, Chestnut and Fire: Climatic and Cultural Controls of Long-term Forest Dynamics in New England, USA*, 29 J. BIOGEOGRAPHY 1359, 1369 (2002). *See generally* Donald McKenzie et al, *Climate Change, Wildfire, and Conservation*, 18 CONSERVATION BIOLOGY 890 (2004); A. Joy Belsky, *Effects*

specific characteristics of the fire event at that time and place. Furthermore, complex landscape mosaics of post-fire ecosystems in various stages of recovery can determine the spatial extent, location, and timing of future disturbances by modifying potential fire spread, intensity, and ignition sources.[7] Thus, both the causes and consequences of fire events are fundamentally geographic.

Global pyrogeography has been defined as the study of the spatial distribution of fire across the planet, with specific reference to understanding the constraints on this distribution.[8] Both fuel availability and climate have been shown to govern the distribution of fire at the global scale, largely determining spatial patterning of fire-prone and non-fire-prone regions.[9] Similarly, at finer, landscape scales, the identification of constraints on fire patterning can also be a useful perspective for understanding the causes of fire distribution and subsequent fire effects.[10] Landscape approaches to pyrogeography can be used to understand the spatially contingent causes and consequences of current and future fire distributions at scales that are relevant to land management decisions.

Understanding spatial patterns of fire regimes is a current, interagency research objective. The creation of standardized tools, such as the Fire Regime Condition Class (FRCC)[11] to map the degree of departure of current fire regimes from reference conditions at continental scales are used to guide objectives and set priorities for fire management treatments. Similarly, the LANDFIRE National Fire Regime Group, in conjunction with The Nature Conservancy, has mapped five dominant fire regimes across the conterminous United States. These fire regimes span three dominant fire return intervals (0 years to 35 years, 35 years to

---

of Grazing, Competition, Disturbance and Fire on Species Composition and Diversity in Grassland Communities, 3 J. VEGETATION SCI. 187 (1992).

[7] *See generally* Jian Yang et al., *Spatial Controls of Occurrence and Spread of Wildfires in the Missouri Ozark Highlands* 18 ECOLOGICAL APPLICATIONS 1212 (2008); Monica Mermoz et al., *Landscape Influences on Occurrence and Spread of Wildfires in Patagonian Forests and Shrublands* 86 ECOLOGY 2705 (2005); David A. Perry et al., *Forest Structure and Fire Susceptibility in Volcanic Landscapes of the Eastern High Cascades*, 18 CONSERVATION BIOLOGY 913(2004).

[8] *See generally* Meg A. Krawchuk et al., *Global Pryogeography: The Current and Future Distribution of Wildfire*, 4 PLoS ONE 4 (2009) *available at* http://www.plosone.org/article/info:doi%2F10.1371%2Fjournal.pone.0005102.

[9] *Id.*

[10] *See generally* Vigdis Vandvik et al., *Managing Heterogeneity: The Densities Following the 1988 Fires in Yellowstone National Park*, 42 J. APPLIED ECOLOGY 139-(2005); Daniel M. Kashian et al., *Spatial Heterogeneity of Lodgepeople Pine Sapling Densities Following the 1998 Fires in Yellowstone National Park*, 34 CAN.J.FOR.RES. 2263 (2004) [hereinafter Kashian, *Spatial*].

[11] *See generally* Fire Regime Condition Class, http://www.frcc.gov (last visited Apr. 11, 2010).

199 years, and 200 or more years) and three fire severities (low, mixed, high).[12] A majority of northeastern United States forests are categorized as Group V (200 or more fire return interval, including a range of low, mixed, and high severity fires), although Group III (35 year to 200 year frequency, low to mixed severity) are also present throughout. Thus, current maps of fire regimes in the Northeast suggest fire frequencies of as little as 35 years to greater than 200 years, and the full suite of fire severities, suggesting substantial heterogeneity across the region.

Despite significant progress in mapping and describing increasingly discrete categorization of fire regimes that vary spatially, general grouping of fire regimes based on frequency and lethality into three classes ("understory," "mixed," and "stand-replacing") is a useful metric for understanding variation in fire regimes and their effects at broad scales.[13] Understory fire regimes are generally characterized by frequent (1 year to 35 years), low severity fires. Fires tend to travel on the ground and trees are not killed due to the combination of lower intensity of combustion and fire adaptations such as thick bark that protects the tree from understory flames. In forests, these regimes have been historically comprised of, for example, low elevation, dry ponderosa pine and southeastern coastal plain vegetation types. These ecosystems have been strongly influenced by fire suppression because (1) the incidence of fire suppression activities in these areas has been extensive, and (2) the fire interval is short relative to the length of the suppression period, resulting in several 'missed' fires, leading to large fuel accumulations relative to historical conditions.[14]

In contrast, stand-replacement fire regimes represented infrequent (100 years to 200 or more years), high severity fires that travel through the forest canopy and which result in complete tree (and stand) mortality. These fires are driven largely by extreme climate events,[15] and are less responsive to changes in fuel loading. Fire suppression has had a relatively smaller effect on these systems because (1) these forests tend to be located on high elevation, historically dense, cool coniferous forests, where suppression activities are more difficult to implement, and

---

[12] *See* Landfire National Product Descriptions, http://www.landfire.gov/NationalProductDescriptions12.php (last visited Apr. 11, 2010).

[13] *See* James Agee et al., *Annual And Decadal Climate Forcing Of Historical Fire Regimes In The Interior Pacific Northwest, USA*, 12 THE HOLOCENE 597, 598 (2002). *See generally* Tania Schoennagel et al., *The Interaction of Fire, Fuels, And Climate Across Rocky Mountain Forests*, 54 BIOSCIENCE 663 (2004) [hereinafter Schoennagel, *Fire, Fuels, and Climate*]; Reed Noss, *Managing Fire-Prone Forests In The Western United States*, 4 FRONTIERS IN ECOLOGY AND THE ENV'T 483 (2006).

[14] *See generally* Schoennagel, *Fire, Fuels, and Climate*, *supra* note 13.

[15] *See* Anthony L. Westerling et al., *Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity*, 313 SCI. 940, 941-43 (2006).

(2) the period of active fire suppression has been short relative to the historical fire cycle.[16]

In between these two extremes are "mixed-severity" fire regimes that represent intermediate fire severities and frequencies across space and time. These systems are exemplified by increased level of patchiness in fire severity, including partial tree kill as well as understory burning. Fire frequency is intermediate, between stand-replacement and understory burning, ranging from 25 years to 75 years.[17] As a result, the effect of fire suppression on fuel accumulation is varied depending on the fire histories of specific locations. These forests are typified, for example, by cool fir forests in southern Oregon and northern California.

As a result of the wide variation in fire regimes in the United States, caution must be used when administering policy under a "one size fits all" solution.[18] Instead, understanding the geography of fire regimes is critical for the efficient implementation of fire management policies. In this context, framing of fire management strategies in the context of historical management trajectories is critical. Similarly, recognition of spatial contingencies—both social and ecological—will be important for developing relevant fire management plans. These considerations are particularly pertinent given the range of forests and forest conditions of the northeast, including differential historical legacies of fire distributions and land use, and variable patterns in forest types ("fuels") and climate.[19]

B. *The Climate of Fire*

Although human manipulation of fire regimes is widespread, climate remains a dominant control on the amount of land area burned.[20] For example, Littell[21] showed that the wildfire area burned in the western United States between 1916 and 2003 was dominated by climate patterns, despite the fact that this time period represents a period of active fire suppression. Similarly, in the subalpine portions of the Rocky

---

[16] *See generally* Schoennagel, *Fire, Fuels, and Climate*, *supra* note 13.

[17] *See generally* Agee et al., *supra* note 13.

[18] *See* Richard T. Brown et al., *Forest Restoration and Fire: Principles in the Context of Place*, 18 CONSERVATION BIOLOGY 903, 904 (2004); Schoennagel, *Fire, Fuels, and Climate*, *supra* note 13, at 663; Noss, *supra* note 13, at 482.

[19] *See* Foster et al., *supra* note 6, at 1369.

[20] *See* Jeremy S. Littell, *Climate and Wildfire Area Burned in Western United States Ecoprovinces*, 19 ECOLOGICAL APPLICATIONS 1003, 1003-04 (2009); William J. Bond et al., *The Global Distribution of Ecosystems in a World Without Fire*, 165 NEW PHYTOLOGIST 525, 525-26 (2005).

[21] *See* Jeremy S. Littell et al., *Climate and Wildfire Area Burned in Western U.S. Ecoprovinces, 1916-2003*, 19 ECOLOGICAL APPLICATION 1003, 1015-16 (2009).

Mountains, wildfire occurrence has been correlated with increased spring and summer temperatures and an early spring snowmelt.[22]

In the future, regional changes in climate can lead to altered fire behaviors and distributions by modifying the energy and water limitations that constrain fire occurrence.[23] Specifically, modifications of energy and water that drive fire patterns occur via (1) modifications in fuel quantity through increases or decreases in vegetation productivity, (2) shifts in species distributions or vegetation types that alter fuel structure and arrangement, or (3) changes in the quantity and seasonal distribution of precipitation, and vegetative evaporative demands, which together alter fuel moisture contents. Additionally, wildfire occurrence is dependent on ignition sources, which can be affected by increases or decreases in storm activity even in the absence of human modifications of ignition potential.

Modeled estimates suggest that projected changes in climate are likely to lead increases in the area burned. For example, the area burned in the Boreal Forest Natural Region of Alberta, Canada increased 12.9 % and 29.4% under 2 x CO_2 and 3 x CO_2 emissions scenarios compared to the baseline 1 x CO_2 levels.[24] In the western United States, current climate projections suggest that by the end of the Twenty-First Century, conditions like those of 1988 (the year of the well-known Yellowstone fires) will represent close to the *average* year rather than an extreme year.[25] These model simulations suggest that historical representations of fire regimes—their seasonality, spatial distribution, and severity—are likely to not represent future conditions. As a result, forecasting the direct and indirect effects of climate on future fire regimes will be necessary for guiding future fire policy in the northeast.

C. *The Fuel of Fire*

Fundamental to understanding fire severity is an understanding of fuel loads, fuel flammability, and fuel connectivity. For a fire to carry across an ecosystem, the vegetation must be dry enough to ignite, be connected enough to propagate heat to adjacent fuels, and exist in sufficient quantities to sustain the burn. These characteristics vary internally based on the chemical signature of the vegetation itself.[26] Vegetation characteristics that affect fire also vary structurally in both

---

[22] *See* Westerling et al., *supra* note 15, at 941-43.

[23] *See* Littell et al., *supra* note 21, at 1019.

[24] *See* Cordy Tymstra et al., *Impact of Climate Change on Areas Burned in Alberta's Boreal Forest,* 16 INT'L J. WILDLAND FIRE 153, 157 (2007).

[25] A.M. Westerling, unpublished data.

[26] *See* Fiona R. Scarff & Mark Westoby, *Leaf Litter Flammability in Some Semi-arid Australian Woodlands*, 20 FUNCTIONAL ECOLOGY 745, 749 (2006).

vertical and horizontal dimensions and can be dramatically influenced by forest management.[27] Of particular concern in forests where fire has been suppressed is the development of "ladder" fuels that can carry a ground fire into the upper canopy by increasing vertical complexity and connectivity of fuels. Additionally, the amount of *horizontal* connectivity of fuels in the canopy and the ground surface can determine whether a fire can spread across landscapes.

Critically, these fuel characteristics vary across species and with successional stages in forest development. Fuel models have been developed as a way to classify vegetation types with similar fire behavior characteristics.[28] These classifications, in conjunction with other information such as weather and topography, are often used to drive fire behavior models and have dramatically increased the ability of fire managers to replicate or project future fire behavior across diverse ecosystems. Modifications of fuel structure and fuel composition through past forest management, including fire suppression has been shown to modify current fire behavior with resulting shifts in carbon fluxes to the atmosphere.[29]

Moreover, climate change is likely to lead to shifts in potential species distributions, and potentially to novel combinations of species that have not been replicated in the paleoclimatic record.[30] Given the acknowledged linkages between fuel composition and structure to fire behavior, these shifts are likely to result in altered fire behavior. As a result, understanding reciprocal interactions between fire regimes and species distributions under future climate scenarios is a critical need for constraining uncertainties in model predictions of forest ecosystems,[31] but these interactions have not been explored fully for the northeastern United States. It is possible that even if climate increases the propensity for severe fire ignitions, shifts in vegetation composition or arrangement may retard fire spread.

---

[27] *See* Brian R. Sturtevant et al., *Human Influence on the Abundance and Connectivity of High-risk Fuels in Mixed Forests of Northern Wisconsin, USA*, 19 LANDSCAPE ECOLOGY 235, 249 (2004).

[28] *See* JOE H. SCOTT & ROBERT E. BURGAN, STANDARD FIRE BEHAVIOR FUEL MODELS: A COMPREHENSIVE SET FOR USE WITH ROTHERMEL'S SURFACE FIRE SPREAD MODEL 4 (U.S. Dep't of Agric., Forest Serv., Rocky Mountain Research Station, 2005).

[29] *See generally* Matthew Hurteau & Malcolm North, *Fuel treatment effects on tree-based forest carbon storage and emissions under modeled wildfire scenarios*, 7 FRONTIERS IN ECOLOGY AND THE ENV'T 409 (2008).

[30] *See* John W. Williams et al., *Projected distributions of novel and disappearing climates by 2100 AD*, 104 PROC. NAT'L ACAD. SCI. U.S. 5738, 5739 (2007).

[31] *See generally* Drew Purves & Stephen Pacala, *Predictive Models of Forest Dynamics*, 320 SCI. 1452 (2008).

II. CASE STUDY ANALYSIS OF PYROGEOGRAPHY

A. *Case Study #1: The Greater Yellowstone Ecosystem*

The Greater Yellowstone Ecosystem (GYE), located in the northwestern Wyoming provides a good case study for exploring the pyrogeography of a stand-replacing fire system to determine how an understanding of geographically explicit causes and consequences of fire can improve fire management policy. The fire regime of the GYE is stand-replacing, with average fire return intervals between 150 and 300 years, largely dependent on variation in elevation.[32] The most common tree species in the region is lodgepole pine (*Pinus contorta* var. *latifolia*), but subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), Engelmann spruce (*Picea engelmannii* Parry), whitebark pine (*Pinus albicaulis* Engelm.) and Douglas-fir (*Pseudotsuga menziesii*) are also present.

Following the large fires of 1988 that burned approximately 35% of Yellowstone National Park, numerous scientific studies have characterized the ecosystem recovery of the post-fire lodgepole pine forests.[33] Briefly, these studies have indicated post-fire ecosystem structure and function is heterogeneous at multiple spatial scales.[34] At the broadest scale, the distribution of past, stand-replacement fires from fire history studies suggests a mosaic of burned patches in various stages

---

[32] *See* Tania Schoennagel et al., *The Influence of Fire Interval and Serotiny of Postfire Lodgepole Pine Density in Yellowstone National Park*, 84 ECOLOGY 2967, 2976 (2003) [hereinafter Schoennagel, *Influence of Fire*].

[33] *See generally* Dan M. Kashian, et al., *Variability in Leaf Area and Stemwood Increment Along a 300-year Lodgepole Pine Chronosequence*, 8 ECOSYSTEMS 48 (2005) [hereinafter Kashian, *Variability in Leaf Area*]; Dan M. Kashian, et al., *Variability and Convergence in Stand Structure with Forest Development on a Fire-dominated Landscape*, 86 ECOLOGY 643 (2005) [hereinafter Kashian, *Variability and Convergence*]; William H. Romme, et al., *Ten Years After the 1988 Yellowstone Fires: Is Restoration Needed?*, *in* AFTER THE FIRES: THE ECOLOGY OF CHANGE IN YELLOWSTONE NATIONAL PARK, (L.L. Wallace ed., Yale University Press, New Haven 2004); Creighton M. Litton, et al., *Soil Surface Carbon Dioxide Efflux and Microbial Biomass in Relation to Tree Density 13 Years After a Stand Replacing Fire in a Lodgepole Pine Ecosystem*, 9 GLOBAL CHANGE BIOLOGY 680 (2003); Monica G. Turner, et al., *Surprises and lessons from the 1988 Yellowstone Fires*, 1 FRONTIERS IN ECOLOGY AND THE ENV'T 351-358 (2003) [hereinafter Turner, *Suprises*]; Monica G. Turner, et al., *Effects of Fire Size and Pattern on Early Succession in Yellowstone National Park*, 67 ECOLOGICAL MONOGRAPHS 411-433 (1997) [hereinafter Turner, *Effects of Fire Size*]; Daniel B. Tinker, et al., *Landscape-Scale Heterogeneity in Lodgepole Pine Serotiny*, 24 CAN. J. FOR. RES. 897 (1994); Monica G. Turner, et al., *Effects of Fire on Landscape Heterogeneity in Yellowstone-National-Park, Wyoming*, 5 J. VEGETATION SCI. 731-742 (1994) [hereinafter Turner, *Effects of Fire on Landscape*]; Kashian, *Spatial*, *supra* note 10; *Schoennagel*, *Influence of Fire*, *supra* note 32.

[34] *See* Tania Schoennagel, et. al., *Landscape Heterogeneity Following Large Fires: Insights from Yellowstone National Park, USA*, 17 INT'L J. WILDLAND FIRE 742 (2008) [hereinafter Schoennagel, *Landscape*].

of recovery.[35] In a stand-replacement fire system, this landscape age-class mosaic reflects the historical legacy of fire on the landscape and can be used to infer spatial and temporal variation in fire frequency. In the case of Yellowstone National Park, fire intervals are longer at higher, cooler elevations compared to lower elevations that tend to be hotter and drier and to burn more frequently.

At intermediate scales, the 1988 fires resulted in heterogeneous patterns in seedling regeneration, with rapid regeneration in some areas.[36] Variation in regeneration was a function of fire severity (although all fires were stand-replacement) and, to a large degree, serotiny—the tendency for cones that release their seeds upon heating. Serotiny is spatially variable among lodgepole pine trees in Yellowstone, but where it was present in the pre-1988 forest, it led to high seedling density and fast, post-fire recovery rates. Across the landscape, variation in recovery patterns resulted in substantial variation in aboveground productivity in the single, post-fire age-class. The range of variation in productivity patterns observed in this single age-class was comparable to the the range of productivity that is often observed through succession.[37]

At fine scales, variation in stand structure in burned stands was variable due to the combination of dead wood, regenerating vegetation, and open areas, which resulted in variation in rates of decomposition of organic matter[38] and rates of soil nutrient cycling.[39] Thus, multi-scale heterogeneity in ecological pattern and process, combined with the rapid recovery of lodgepole pine was therefore a trademark of the Yellowstone fires of 1988.[40] Rather than reducing variation in ecosystem processes, the large fire initiated patterns (stand structure, age-class) that created variation in fundamental ecological processes such as productivity, decomposition, and nutrient cycling.

The stand-replacement fires of the GYE are also useful for guiding fire management through the exploration of those factors that contribute

---

[35] *See generally* William H. Romme and Don G. Despain, *Historical-Perspective on the Yellowstone Fires of 1988*, 39 BIOSCIENCE 695 (1989).

[36] *See generally* Turner, *Effects of Fire on Landscapes*, *supra* note 33, at 731-742; Turner, *Effects of Fire Size*, *supra* note 33, at 411-433.

[37] *See generally* Monica G. Turner, et al., *Landscape Patterns of Sapling Density, Leaf Area, and Aboveground Net Primary Production in Postfire Lodgepole Pine Forests, Yellowstone National Park (USA)*, 7 ECOSYSTEMS 751 (2004).

[38] *See generally* Alysa J. Remsburg & Monica G. Turner, *Amount, Position, and Age of Coarse Wood Influence Litter Decomposition in Postfire Pinus Contorta Stands*, 36 CAN. J. OF FOR. RES. 2112 (2006).

[39] *See* Kristine L. Metzger, et. al, *Influence of Coarse Wood and Pine Saplings on Nitrogen Mineralization and Microbial Communities in Young Post-Fire Pinus Contorta*, 256 FOREST ECOLOGY & MGMT. 59, 65 (2008).

[40] *See* Monica G. Turner, et al., *Surprises and Lessons from the 1988 Yellowstone Fires*, 1 ECOLOGY SOC'Y OF AM. 351, 352-54 (2003).

to ecosystem resilience following disturbance. Resilience is "the capacity of a system to absorb disturbance and reorganize while undergoing change so as to retain essentially the same function, structure, identity and feedbacks."[41] Was the Yellowstone ecosystem resilient in the face of the 1988 extreme fire event? From the perspective of ecosystem recovery at landscape scales, the lodgepole pine forests were resilient as evidenced by rapid, though variable recovery. Chronosequence studies in the area indicate that there is convergence in stand structure among sparse and dense post-fire stands by approximately 100 years, such that mature stands have comparable structure despite their different trajectories of recovery.[42] From the perspective of carbon and nutrient stocks, field studies further suggest that recovery of these pools occurs rapidly in young post-fire stands. By approximately 100 years, and often by about 35 years, carbon and nutrient stocks in post-fire stands are comparable to those in mature stands.[43] This is well within the average fire return interval indicating full recovery of biogeochemical function prior to a subsequent fire event. Rapid recovery of carbon and nutrient stocks is due to the fact that although stand replacement fires kill the forest stand, there is rapid regrowth in many locations. Additionally, relatively little biomass is consumed because the fire is carried through the canopy, leaving large wood stores and soil, the largest stores of carbon in forested systems, intact. Taken together, low amounts of elemental losses, combined with rapid but variable regeneration, suggest that the Yellowstone system is resilient to large, stand-replacing fires.

Whether the Yellowstone landscape is resilient to future fire events in the face of climate change is less certain for several reasons.[44] First, modeling results indicate that the rate of ecosystem recovery is dependent on the specific level of change in precipitation and temperature determined by a given CO_2 emissions scenario. Second, the rate of recovery largely determines whether biomass (or carbon stocks)

---

[41] *See generally* Carl Folke et al., *Regime shifts, resilience, and biodiversity in ecosystem management*, 35 ANN. REV. OF ECOLOGY EVOLUTION AND SYSTEMATICS 557 (2004).

[42] *See generally* Kashian et al., *supra* note 10; *see also* Daniel Kashian et al., *Carbon storage on landscapes with stand-replacing fire*, 56 BIOSCIENCE 598 (2006).

[43] *See* John B. Bradford et al., *Tree age, disturbance history, and carbon stocks and fluxes in subalpine Rocky Mountain forests*, 14 GLOBAL CHANGE BIOLOGY 2882, 2888 (2008). *See generally* Erika Smithwick et al., *Long-Term Nitrogen Storage and Soil Nitrogen Availability in Post-Fire Lodgepole Pine Ecosystems*, 12 ECOSYSTEMS 792 (2009) [hereinafter Smithwick, *Long-Term Nitrogen Storage*]; Erika Smithwick et al., *Modeling the effects of fire and climate change on carbon and nitrogen storage in lodgepole pine (Pinus contorta) stands*, 15 GLOBAL CHANGE 535, 545 (2009) [hereinafter Smithwick, *Modeling*].

[44] *See* Smithwick, *Modeling*, *supra* note 43, at 542.

recovers to pre-fire levels before the end of the projection period (year 2100). Given these two factors, model results indicated that sparsely regenerating stands did not recover their pre-fire stocks before year 2100.[45] This situation would be magnified in management timeframes with even shorter temporal windows. Thus, ecologically, the system would recover and be considered resilient prior to the next fire event; however, the relevant timeframes for ecosystem management may be substantially shorter.

Finally, projections of climate change in the western United States are expected to be more severe than in the past.[46] If the "extreme" fire year of 1988 represents "average" fire conditions of the future, recovery of ecosystems (even given rapid rates of regeneration) is not likely in the face of repeated, severe fire events. In a scenario of limited forest regeneration, ecosystem switches from forest to woodland or grassland systems is likely, with equally dramatic consequences for carbon storage. A simple spreadsheet modeling approach revealed that reductions of mean fire intervals from 150 to 300 years down to 80 years on the Yellowstone landscape only reduced carbon stocks by 6%, indicating very substantial shifts in fire frequency would be necessary to influence carbon storage patterns.[47] However, future scenarios of climate change suggest that these situations are more likely than previously anticipated, indicating that knowledge of past fire regimes (frequency, severity) may be poor guides for the future.

B. *Case Study #2: Eastern Cape, South Africa*

1. Geography of Fire

Globally, biomass burning is a significant source of global atmospheric emissions.[48] Tropical fires may release 2.6 Pg C yr^{-1} and an additional flux of 1.2 Pg C yr^{-1} due to post-fire decomposition of residual

---

[45] *See id.*

[46] *See* Brian Stocks, Johann Goldammer & Leonid Kondrashov, *Impacts of climate change on fire activity and fire management in the circumboreal forest*, 15 GLOBAL CHANGE BIOLOGY 549-60 (2009). *See generally* Anthony L. Westerling et al., *Warming and earlier spring increase western U.S. forest wildfire activity*, 313 SCI. 940 (2006).

[47] *See generally* Dan M. Kashian et al., *Carbon cycling on landscapes with stand-replacing fire*, 56 BIOSCIENCE 598(2006).

[48] *See* Meinrat O. Andreae, *Biomass burning: its history, use, and distribution and its impact on environmental quality and global climate*, *in* GLOBAL BIOMASS BURNING: ATMOSPHERIC, CLIMATIC AND BIOSPHERIC IMPLICATIONS 3-21 (Joel S. Levine ed., MIT Press 1991). *See generally* Mary Scholes & Meinrat O. Andreae, *Biogenic and pyrogenic emissions from Africa and their impact on the global atmosphere*, 29 AMBIO 23 (2000); Wei M. Hao et al., *Emissions of CO2, CO, and hydrocarbons from fires in diverse African savanna ecosystems*, 101 J. GEOPHYSICAL RESEARCH 523 (1996).

biomass.[49] African fires account for 37% of global fire carbon emissions[50] making Africa the "single largest continental source of biomass burning emissions."[51] Williams[52] recently concluded that "Africa is one of the weakest links in our understanding of the global carbon cycle." Specifically, there is considerable uncertainty about the variability in fire occurrence over space and time[53] and limited knowledge of temporal and spatial patterns of carbon stocks and fluxes[54] that may be affected. For example, in addition to carbon losses through combustion, post-fire carbon fluxes are characterized by a period of net carbon flux to the atmosphere due to decreases in plant uptake and increases in decomposition of plant biomass. As the ecosystem recovers, its carbon sequestration capacity increases. The net balance of carbon flux (to or from the atmosphere) across fire-prone landscapes depends, therefore, on the age-class structure of the landscape, patterns in fire severity, and patterns in post-fire recovery. Patterns in severity and recovery are spatially complex across broad landscapes, but these patterns are not well characterized across African landscapes.

Fire also affects, and is affected by, local livelihood strategies[55] that vary spatially across complex socio-ecological landscapes in Africa. For example, fire is used for increasing nutrient quality of grasses for grazers, reducing tick populations, increasing hunting success, poaching, controlling undesirable species, clearing brush, and for fertilizing in traditional forms of agriculture. Lack of fire can lead to bush encroachment, an increase in invasive species, and an increase in extreme, uncontrolled wildfire. Additionally, soil nutrients in fine scales

---

[49] *See generally* Guido R. Van Der Worth et al., *Carbon Emissions from Fires in Tropical and Subtropical Ecosystems*, 9 GLOBAL CHANGE BIOLOGY 547 (2003).

[50] *See* Christopher A. Williams et al., *Africa and the Global Carbon Cycle*, CARBON BALANCE MGMT, Mar. 7, 2007, at 1, 5, http://www.cbmjournal.com/content/pdf/1750-0680-2-3.pdf.

[51] *See generally* Gareth J. Roberts et al., *Annual and Diurnal African Biomass Burning Temporal Dynamics*, 6 BIOGEOSCIENCES 849 (2009).

[52] *See* Williams et al., *supra* note 50.

[53] *See generally* Paulo M. Barbosa et al., *An Assessment of Vegetation Fire in Africa (1981–1991): Burned Areas, Burned Biomass, and Atmospheric Emissions,* 13 GLOBAL BIOECOCHEMICAL CYCLES 933,(1999); Erica A. Hoffa et al., *Seasonality of Carbon Emissions from Biomass Burning in a Zambian Savanna,* 104 J. GEOPHYSICAL RES. 13,841(1999); Van Der Werf et al., *supra* note 49.

[54] Williams et al., *supra* note 50, at 3.

[55] *See, e.g.,* Michael P. Dombeck et al., *Wildlife Policy and Public Lands: Integrating Scientific Understandings with Social Concerns across Landscapes,* 18 CONSERVATION BIOLOGY 883 (2004); Christian A. Kull, *Madagascar Aflame: Landscape Burning as Peasant Protest, Resistance, or a Resource Management Tool?* 21 POL. GEOGRAPHY 927(2002).

and broad-scale climates are debated contributors of variability in fire regimes and savanna vegetation structure.[56]

It is likely that multiple, hierarchical drivers of vegetation dynamics operate simultaneously at a range of scales[57] resulting in complex landscape patterns that govern and respond to fire. Currently, heterogeneity of fire regimes is now at the forefront of new approaches for fire management in African savannas, recognizing that regular burning cycles failed historically to capture the full suite of ecological responses to fire and often led to negative effects such as the loss of indigenous species.[58] In South Africa, an appreciation of pyrocomplexity that recognizes variability in the season, intensity, and frequency of burning, as well as the spatial variability of fire effects, is critical for managing parks and reserve areas with patch-burning fire systems.[59]

The Dwesa-Cwebe and Mkambhathi Nature Reserves in the Eastern Cape of South Africa represent two important case studies of contrasting fire regimes that reflect the complexity of understanding fire distributions in southern Africa. Specifically, the Eastern Cape Province of South Africa is located within the Maputaland-Pondoland-Albany biodiversity hotspot identified by Conservation International for its high tree richness and high degree of plant endemism. Within this vegetative zone, these two reserves represent very different landscapes with contrasting patterns of vegetation and fire. Forests within the Dwesa-Cwebe reserve are classified as Coastal Lowland Forest with relatively long fire frequencies (up to 100 years). Small grassland patches are maintained by more frequent burning, but are interspersed within a

---

[56] *See generally* Anthony J. Mills et al., *A Framework for Exploring the Determinants of Savanna and Grassland Distribution*, 56 BIOSCIENCE 579(2008); Joanna I. House et al., *Conundrums in mixed woody-herbaceous plant systems*, 30 J. BIOGEOGRAPHY 1763(2003).

[57] *See generally* Sally Archibald, *African Grazing Lawns—How Fire, Rainfall, and Grazer Numbers Interact to Affect Grass Community States*, 72 J. WILDLIFE MGMT. 492 (2008); Samuel D. Fuhlendorf & David M. Engle, *Application of the Fire-grazing Interaction to Restore a Shifting Mosaic on Tallgrass Prairie*, 41 J. APPLIED ECOLOGY 604 (2004); David J. Augustine et al., *Feedbacks Between Soil Nutrients and Large Herbivores in a Managed Savanna Ecosystem*, 13 ECOLOGICAL APPLICATIONS 1325 (2003).

[58] *See generally* THE KRUGER EXPERIENCE: ECOLOGY AND MANAGEMENT OF SAVANNA HETEROGENEITY PARADIGM (Harry C. Biggs et al. eds., Island Press, 2003) [hereinafter THE KRUGER EXPERIENCE]; Kevin H. Rodgers, *Adopting a Heterogeneity Paradigm: Implications for Management of Protected Savannas*, *in* THE KRUGER EXPERIENCE: ECOLOGY AND MANAGEMENT OF SAVANNA HETEROGENEITY PARADIGM 41 (Harry C. Biggs et al. eds., Island Press, 2003).

[59] *See generally* THE KRUGER EXPERIENCE, *supra* note 58.

dominantly forested matrix.[60] In contrast, Mkambhathi is dominated by grasslands that experience frequent fire (one to five years) and are grazed heavily by resident herbivores such as zebra, kudu, and blesbok. Isolated patches of forest are present within the reserve, which apparently have not burned for several decades. Thus, although both reserves are located in similar climatic zones, and both are represented by similar species composition, the relative balance of trees versus grass is determined by a complex interplay among fire frequencies, grazing, and potentially other factors such as nutrient cycling and soil characteristics. Additionally, livelihood strategies differ among communities surrounding each park. Poaching is a key determinant of fire patterns in Mkambhathi, as local communities will use fire to draw animals closer to park boundaries to access the nutrient-rich post-fire grasses, where they are more easily poached. In contrast, Dwesa-Cwebe is dominantly forested with a much lower herbivore/grazer community, and local communities depend on marine resources in the associated intertidal coastal zone more than poaching to meet protein demands. As a result, the grass mosaic in Mkambhathi is characterized by high fire frequencies that are maintained by people burning for herbivores, thus reinforcing the dominance of grasses in the landscape.

2. Climate of Fire

At a continental scale, potential climate trends for southeastern South Africa indicate the region may become drier in the future, depending on the season, but there is little model agreement.[61] Of particular interest, shifts in precipitation seasonality may alter seasonal fuel loads and change temporal trends in fire severity. Analysis of high resolution gridded data suggests that some of the uncertainty in the GCM projections of rainfall over South Africa is due to differences in GCM parameterization schemes. Using downscaling procedures, uncertainties in climate projections are reduced, resulting in greater model agreement.[62] These projections indicated increased summer rainfall over a large portion of eastern South Africa during the summer (December, January, February) season. This is typically the "wet" season, indicating

---

[60] *See generally* Graham I. H. Kerley et al., *Desertification of Subtropical Thicket in the Eastern Cape, South Africa: Are there Alternatives?*, 37 ENVTL. MONITORING & ASSESSMENT 211 (1995).

[61] *See generally* Jens H. Christensen et al., *Regional Climate Change Projections, in* CLIMATE CHANGE 2007: THE PHYSICAL SCIENCE BASIS 847 (Susan Solomon ed., Cambridge University Press 2007).

[62] *See generally* Bruce C. Hewitson & Robert G. Crane, *Consensus between GCM climate change projections with empirical downscaling: Precipitation downscaling over South Africa*, 26 INT'L J. CLIMATOL. 1315 (2006).

increased precipitation during time periods where rainfall is not limiting, a pattern which is not likely to reduce fire hazard during the winter when fire is more common. In contrast, increases in fuel load due to increases in precipitation during the summer could potentially increase fire hazard during the dry season.

3. Fuel of Fire

As indicated by the previous discussions, patterns of fuels are spatially diverse and largely governed by interactions of climate and fire. However, recent modeling work suggests that patterns in vegetation are driven largely by the presence or absence of fire, especially in southern Africa. Specifically, the importance of fire for structuring African landscapes suggests that savannas would transition to forests if fire were excluded.[63] Understanding specific trajectories of change due to altered climate, in conjunction with the associated drivers of fire across the region, described above, will be critical for describing and projecting future fuel conditions across the region.

III. LESSONS FOR THE NORTHEAST

A. Climate

In the most recent IPCC assessment, projected changes in mean annual temperature for eastern North America are expected to range from 2°C to 6°C, depending on CO_2 emission scenario, averaging around 4°C for the A1B scenario.[64] Annual precipitation is expected to increase in the northeastern United States.[65] However, seasonal variations in precipitation across the northeastern United States are unclear due to disagreement across simulation models. For example, although there is relatively higher confidence for increases in winter precipitation in the northeast (17 to 18 models out of 21 agree), half of the models project summer increases in precipitation, while half project decreases.[66]

Impacts for specific locations provide a deeper context for understanding shifts in average climate and variability. For example, The Pennsylvania Climate Impacts Assessment recently summarized climate impacts for the state based on available literature.[67] Climate

---

[63] *See generally* William J. Bond et al., *The Global Distribution of Ecosystems in a World Without Fire*, 165 NEW PHYTOLOGIST 525 (2005).

[64] *See* Christensen et al., *supra* note 61, at FIG. 11.11.

[65] *See id.* at FIG. 11.12.

[66] *See id.*

[67] *See generally* James S. Shortle et al., PENNSYLVANIA CLIMATE IMPACT ASSESSMENT REPORT TO THE DEPARTMENT OF ENVIRONMENTAL PROTECTION (June 29,

projections used to frame this report suggested several important climate trends that have relevance for understanding future fire in the northeast. Specifically, it is very likely that Pennsylvania will warm (7°F) and that annual precipitation will increase, especially in winter. At the same time, it is likely that Pennsylvania's precipitation will become more extreme, with longer dry periods and greater intensity of precipitation. Reductions in snow covered days per month in December to February is also likely to change in future periods compared to the historical reference period (1961 to 1990). Changes depend on the specific emission scenarios and future time period analyzed, but decreases of ten days of snow-cover are expected across much of the northeast.

Increases in winter precipitation could increase fuel loads, increasing the potential for higher fire severity in the northeast. Similarly, more extreme dry periods in the late summer/fall, when fuel loads are dormant, could increase the potential for fire risk. Finally, earlier snowmelt could decrease hydrologic flows and increase drought conditions in the late summer, while simultaneously increasing the length of the potential fire season. Taken together, model projections suggest that the future climate of the northeast will be more conducive to increased fire activity than has been observed in the recent past. However, actualized increases in fire activity must be considered in their geographical context and must be considered along with variation in fuel loads, flammability, climate, ignition sources, and departure historical from fire regimes. Moreover, climate scenarios are dependent on the future time frame that is considered, i.e., next 20, 50, or 100 years, and the specific CO_2 emission scenario.

B. Fuels

Terrestrial vegetation in the northeastern United States is heterogeneous and it can be categorized at many levels, including biome, forest type, and species composition. The terrestrial biomes of the northeastern United States include subalpine forests in northern Maine, temperate coniferous forests in high elevation areas, cool mixed forests in much of southern New England, and temperate deciduous forests in southern Pennsylvania, New Jersey, and Delaware.[68] This mixture of

---

2009) *available at* http://www.green.psu.edu/resources/pdfs/climateImpactAssessment.pdf.

[68] *See generally* James M. Lenihan et al., *Simulated Response of Conterminous United States Ecysystems to Climate Change at Different Levels of Fire Suppression, CO_2 Emission Rate, and Growth Response to CO_2*, 64 GLOBAL AND PLANETARY CHANGE 20 (2008).

biomes reflects both latitudinal and elevational gradients in climate.[69] A myriad of forest types are represented within these biomes: white/red/jack pine, spruce/fir, longleaf/slash pine, loblolly-shortleaf pine, oak pine, oak/hickory, oak/gum/cypress, elm/ash/cottonwood, maple/beech/birch, and aspen/birch.[70] Current affinities for fire vary across these forest types, with some forest types historically associated with fire, such as oak/hickory, and others having increased fire vulnerability such as maple/beech/birch. The current transition zone between southern species that are more fire-prone and more northerly species that are increasingly fire-sensitive is located in central Pennsylvania.

Associated with shifts in climate described above, the spatial distribution of these vegetation types are projected to change, likely resulting in associated shifts in vegetation-dependent fire characteristics. At a coarse scale, dynamic global vegetation models (DGVMs) predict northward migration of dominant biomes under future climate scenarios in the eastern United States, with temperate deciduous forests replacing cool mixed forests.[71] More specifically, the potential range of maple/beech/birch forests of northern Pennsylvania and parts of southern New England is expected to move northward, to be replaced by oak/hickory forests. Loblolly/shortleaf pine and oak/pine forest types are projected to increase their potential range in much of Maryland/Delaware and much of Virginia.

At a species level, Iverson[72] recently projected changes for 134 species across the eastern United States, similarly reporting a general trend of more southerly species moving into northern locations. Changes between current and future conditions (the average of three GCMs running low CO_2 emissions scenarios or three GCMs running high CO_2 emissions scenarios) were calculated to explore the specific species shifts that are likely to be associated with changes. Results show that the distribution model (described below) predicts *decreases* in the importance value and spatial extent of American beech, balsam fir, chestnut oak, eastern hemlock, red spruce, red maple, sugar maple, and sweet birch, with large *increases* for black hickory, loblolly pine, and shortleaf pine. However, there is *significant regional variation* in

---

[69] *See id. See generally* Charles V. Cogbill & Peter.S. White, *The latitude-elevation relationship for spruce-fir forest and treeline along the Appalachian mountain chain.* 94 VEGETATIO 153(1991).

[70] *See generally* Shortle, *supra* note 67.

[71] *See generally id.*

[72] *See generally* Louis R. Iverson et al., *Estimating potential habitat for 134 eastern US tree species under six climate scenarios*, 254 FOREST ECOLOGY AND MGMT. 390 (2008).

species-specific trends across the northeast. For example, southern species associated with fire (loblolly pine and shortleaf pine) show large increases from Georgia through Virginia, and fire tolerant species like chestnut or oak extend their ranges north even though their total area decreases. Fire-sensitive species such as sugar maple and American beech both show significant shifts north with reduced southern presence. For example, at present only 40% of the occupied area of sugar maple is located north of Massachusetts and that percentage is predicted to increase to 75% under a high emissions scenario. If these preliminary model results on a subset of species are representative of potential changes in vegetation along the transect, it follows that northeastern forests that currently experience relatively long fire return intervals (up to 1000 years) are likely to be replaced partially by vegetation that currently is associated with more frequent fire (3 to 35 years). More frequent fire resulting from altered vegetative structures and/or climate conditions may result in a positive feedback that reinforces the further northward migration of southern, fire-prone species.

IV. IMPLICATIONS FOR POLICY

Lessons from sub-Saharan Africa and the western United States are not directly transferrable to forest policy in the northeastern United States. Differences in climate, ignition sources, vegetation composition, and historical legacies differ widely across these three geographic locations. Yet, the contrast of a frequently burned grassland/woodland mosaic with an infrequently burned, stand-replacing fire regime in subalpine coniferous forest—in many ways the endpoints of a forest-climate-vegetation continuum—provides a rich context for evaluating generalities across systems. To what extent can lessons be drawn from each of these systems that are distinct from their specific geographic contingencies? What are the scientific generalities in each of these systems that can be useful for guiding fire policy in the northeast? Here I provide some overarching scientific considerations, rooted in fire ecology and landscape science, that have guided fire policy in these regions and which are likely to be useful in reconsiderations of the role of fire in the northeast. Rather than describing prescriptions per se, these considerations are useful in the context of managing complex, dynamic landscapes in the face of future change, for constraining and guiding management options, and for recognizing the delicate balance between ecosystem management and function.

A. *Confront Generalities Across a Variety of Ecosystems and Disturbance Regimes*

Fire policy in the northeast should recognize that fire regimes are place-specific. As such, fire policy meant to guide these fire patterns must be similarly appreciative of spatial dependencies that reflect historical legacies, vegetation patterns, and relevant ecological processes. As described for landscapes in the western United States,[73] emergent fire policy must remain flexible to adapt to the geographically explicit context; one size does not fit all. In this framework, the scale of relevant fire policies should match the scale of the mapped fire pattern. While the particularities of the northeast fire "story" are different from those of other regions nationally and internationally, the northeast itself is heterogeneous at finer scales than that of the region. Similarly, fire policies must reflect heterogeneous patterns at fine scales within the northeast region.

B. *Enable Conditions that Promote Resiliency in the Face of Change*

The development of effective fire policies necessitates the anticipation of future fire regimes and the specific mechanisms that govern fire distributions. Recognition of historical patterns and trends is useful for framing historical ranges of variability,[74] which are helpful for anticipating trajectories of change. For example, comparing suppression timeframes with historical frequencies of fire regimes can guide decision-making about which locations are in need of fuel reduction treatments.[75] Uniformitarianism—that the present is the key to the past, implied by work of James Hutton[76] and later codified by Charles Lyell (1830) – is an oft used conceptual framework to characterize present patterns by inferring past dynamics. Current reasoning, however, has challenged whether the past is a good proxy for future climates[77] or

---

[73] *See generally* Brown et al., *supra* note 18; Schoennagel, *Fire, Fuels, and Climate*, *supra* note 13; Noss et al., *supra* note 13.

[74] *See generally* Rebecca Kennedy & Michael Wimberly, *Historical Fire and Vegetation Dynamics in Dry Forests of the Interior Pacific Northwest, USA, and relationships to Spotted Owl Habitat Conservation*, 258 FOREST ECOLOGY AND MGMT. 554 (2009); Robert E. Keane et al., *Climate Change Effects on Historical Range and Variability of Two Large Landscapes in Western Montana, USA*, 254 FOREST AND ECOLOGY MGMT. 375 (2007); Michael C. Wimberly et al., *Simulating Historical Variability in the Amount of Old Forests in the Oregon Coast Range*, 14 CONSERVATION BIOLOGY 167 (2000).

[75] *See* Brown, *supra* note 18, at 907-08.

[76] Matt Rosenberg, *Uniformitarianism*, ABOUT.COM, (April 7, 2010) *available at* http://geography.about.com/od/physicalgeography/a/uniformitarian.htm.

[77] *See* William W. Hay et al., *Climate: Is the Past the Key to the Future?*, 86 INT'L J. EARTH SCI. 471, 485, 487-88 (1997).

future vegetation patterns[78] in the context of rapid environmental change. Rather, projections of future conditions, based on sound science of the underlying mechanisms, are needed to project future conditions that may vary widely from the past. A key goal of restoration, generally, is therefore to manage landscapes to be sustainable in the future, not the past.[79]

The "future" is never fully known a priori, thus the question emerges as to how to manage in the context of such unpredictability. Models represent a key tool for projecting alternative scenarios of change and should form the foundation of policy development based on science. Critically, however, these models must be evaluated in the context of their underlying structure, assumptions, application domain, and parameterization. Scenarios of climate change are often driven by carbon emissions scenarios developed by the international scientific community, but these scenarios represent anticipated trajectories of change and may not represent the bounds of future climate conditions if underlying assumptions about emissions trends are confronted by the reality of higher or lower fluxes. Critical to this understanding is the quantification and mapping of uncertainty of model results and/or policy outcomes such that policy can be guided with an explicit—rather than implicit—recognition of probabilistic outcomes.

C. *Manage for Key Ecological Functions.*

Fires govern the distribution of vegetation patterns[80] as well as other key ecological functions such as nutrient cycling[81] and carbon storage.[82] Because fire modifies carbon fluxes between the terrestrial biosphere and

---

[78] *See generally* Williams et al., *supra* note 30.

[79] *See generally* Young D. Choi, *Restoration Ecology to the Future: A Call for New Paradigm*, 15 RESTORATION ECOLOGY 351 (2007).

[80] *See* Richardo M. Holdo et al., *Grazers, Browsers, and Fire Influence the Extent and Spatial Pattern of Tree Cover in the Serengeti*, 19 ECOLOGICAL APPLICATIONS 95, 107 (2009); *see also* Kennedy & Wimberly, *supra* note 74, at 563-564.

[81] *See* Shiqiang Wan et al., *Fire Effects on Nitrogen Pools and Dynamics in Terrestrial Ecosystems: A Meta-Analysis*, 11 ECOLOGICAL APPLICATIONS 1349, 1349 (2001); *see also* Giacomo Certini, *Effects of fire on properties of forest soils: a review*, 143 OECOLOGIA 1, 5 (2005). *See generally* Erica A. H. Smithwick et al., *Postfire Soil N Cycling in Northern Conifer Forests Affected by Severe, Stand-Replacing Wildfires*, 8 ECOSYSTEMS 163 (2005).

[82] *See generally* Michael Balshi et al., *Vulnerability of carbon storage in North American Boreal forests to wildfires during the 21st century*, 15 GLOBAL CHANGE BIOLOGY 1491 (2009); Werner Kurz et al., *Risk of natural disturbances makes future contribution of Canada's forests to the global carbon cycle highly uncertain*, 105 PROC. NAT'L ACAD. SCI. U.S. 1551 (2008); Erica Smithwick et al., *Changing temporal patters of forest carbon stores and net ecosystem carbon balance: the stand to landscape transformation*, 22 LANDSCAPE ECOLOGY 77 (2007).

the atmosphere, recognizing shifts in fire regimes is critical for projecting future carbon sequestration.[83] Increased fire disturbances will dramatically change the age-class distribution of western forests, increasing the area of young forest on the landscape and reducing the amount of forest in older age-classes. Similarly, a lack of understanding of disturbance dynamics at regional to global scales currently limits our ability to model feedbacks between the terrestrial biosphere and the climate system.[84]

---

[83] *See generally* William de Groot et al., *Estimating direct carbon emissions from Canadien wildland fires 1*, 16 INT'L J. OF WILDLAND FIRE 593 (2007); Werner Kurz & Michael Apps, *A 70-Year Restrospective Analysis of Carbon Fluxes in the Canadian Forest Sector*, 9 ECOLOGICAL APPLICATIONS 526 (1999).

[84] *See generally* Purves & Pacala, *supra* note 31, at 1452.